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Short communication

Effect of complex combined loading mode on the fracture toughness of titanium alloys

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ABSTRACT

This paper presents new experimental data concerning the effect of the complex combined loading mode on changes in the mechanical properties of titanium alloys of different classes subjected to static stretching. The complex combined loading mode consists in the application of additional pulse loads for given degrees of static pre-loading followed by quenching of titanium alloys at a temperature of liquid nitrogen under a pre-set scheme. The authors used a new method for studying the material fracture kinetics, the so-called method of complete stress-strain diagrams, to explore a full range of mechanical properties of titanium alloys subjected to the combined loading mode, including the crack resistance.

1. Introduction

Prediction of changes in the mechanical properties of promising titanium alloys under thermomechanical action is fundamentally important in order to choose the optimal technological operations to be performed under the combined loading mode [1,2], in which the mechanical properties of alloys, especially plastic deformation and fracture toughness, can be greatly improved.

The authors have previously shown [3,4] that when applying additional load pulses to the base loading, the dynamic non-equilibrium processes (DNP) occur in materials, after which the thin-stripe dissipative structures are formed, the density of which is less than that of the base material. As a result, in most cases, the plastic deformation of materials increases significantly during the subsequent static tension, while the strength remains practically unchanged. Unfortunately, using the stress-strain diagrams after the application of the combined loading mode does not allow for evaluation of the material fracture toughness, which is important for practical applications. We used a new method for studying the kinetics of material fracture in the present study, the so-called method of complete stress-strain diagrams. This approach made exploring possible of a full range of the mechanical properties of titanium alloys of different classes subjected to the combined loading mode [5,6], including the characteristics of fracture toughness. Previously, this method was theoretically and experimentally substantiated by professors A.A. Lebedev and N.G. Chausov [7,8]. They were also the first to propose, based on the analysis of complete stress-strain diagrams, a new characteristic to evaluate the ultimate damage in the plastic part of a complete stress-strain diagram after any pre-loading, which has the meaning of the specific work to fracture, and to develop a new criterion for fracture toughness K_λ.

During the realization of a complete stress-strain diagram, the material resists deformation and fracture at all stages, including the stage of nucleation and propagation of a macro-crack in the material. It is essential, when using the method of complete stress-strain diagrams, that all the operations of the complex combined loading are performed on identical standard small specimens. The same specimens are also used to evaluate the variation of the mechanical properties of titanium alloys, including the characteristics of fracture toughness under the following static tensile load.

2. Materials and methods

The authors used the combined loading, which included the application of additional force pulse to the base loading in their previous research aimed at a significant increase in the material plasticity at room temperature. In this case, the processes of

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List of symbols

σ	stress
ε	strain
t	time
$R_{0.2}$	yield strength
Rm	ultimate strength
δ	relative elongation
E	elasticity module
F_k	loading the specimen, which corresponds to the start of macrocrack
A_0	initial cross-sectional area of the specimen
S_k	cleavage resistance of material
K_λ	parameter of fracture toughness
Δl_e	elastic elongation of the specimen at the time of the start of macrocrack
Δl_p	total elongation of the specimen at the stage of crack growth
$\overline{\Delta l_p}$	the value normalised by bringing to the starting area of the standard specimen section

material deformation and fracture are studied within a mechanical system that includes two contours. The internal contour is the simple statically indeterminate structure in the form of three parallel elements loaded simultaneously: the central specimen from the test material and two symmetrical satellite specimens from fragile steel.

The outside contour includes gripping of the test setup, columns and the hydraulic system of the test setup.

With the controlled fracture of the satellite specimens of the internal contour, the pulsed load is transmitted to the outside contour of the test setup, and the test specimen together with the outside contour of the test setup is subjected to additional load pulses applied to the base loading (impact-oscillatory loading) at a frequency of 1–2 kHz [9], Fig. 1.

Additional studies conducted on titanium alloys showed that under a short-term deep cooling in liquid nitrogen, residual effects associated with changes in the structure of titanium alloys of various classes differ significantly, and their density differs accordingly.

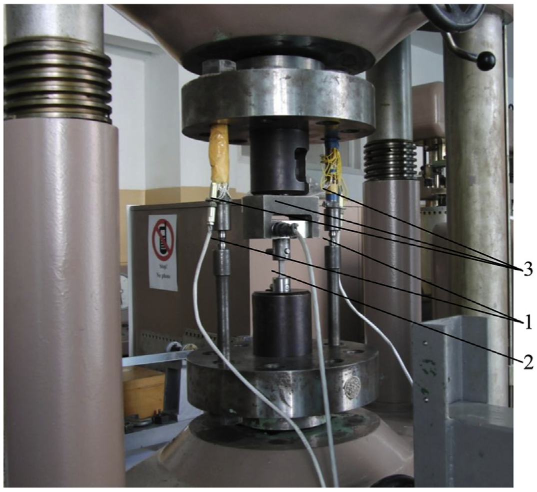

Fig. 1. General view of appliance for realization of impact-oscillatory loading; 1–“brittle” specimens; 2–central specimen; 3–dynamometers.

Research on high-strength VT-22 titanium alloy, which was conducted using this method, has shown that by varying the degree of the static pre-straining and the intensity of force pulse, one can attain a significant increase in plastic deformation under subsequent static tensile load of the alloy compared to its initial state [10]. The optimum mode was established for the standard complex loading conditions of the VT-22 titanium alloy, i.e. “sample standard static tension to the predetermined stress and deformation level – short-term high force loading”, using which the overall plastic deformation of the alloy can be increased by 2.75 times compared to the standard static tension without a substantial loss of strength properties.

Physical research revealed that the microstructure of VT-22 titanium alloy was refined significantly after the application of the impact-oscillatory loading, due to which fine grains were formed within the base of the alloy, leading to the refinement of the subgrains within the same base. This paper presents the results of the tests that were all performed at room temperature.

Therefore, the imposition of low-temperature effects on the pulse introduction of energy into the titanium alloy under impact-oscillatory loading, can also significantly affect the variation of the mechanical properties of titanium alloys of different classes during the following static tensile load at room temperature. In this case, we speak about the optimal complex combined loading mode, at which a significant increase in the plastic deformation of titanium alloys can be achieved, and, possibly, fracture toughness, without appreciable changes in their strength properties. In this paper, studies were conducted on high-strength VT-22 titanium alloy and VT-15 medium-strength titanium alloy. Whereas the combined loading of titanium alloys involved not only the application of additional force pulse to the base loading but rapid short-term cooling of alloys at liquid nitrogen temperatures under a pre-set scheme. Mechanical tests were conducted on flat specimens 3 mm thick (Fig. 2).

The mechanical properties and the chemical composition of the alloys are given in Tables 1 and 2.

3. Result and discussion

Below are the test results for titanium alloys investigated under the complex combined loading, including the short-term cooling mode at liquid nitrogen temperatures under a pre-set scheme.

In this paper, five loading modes were used:

1. Static stretching of specimens from the investigated alloys in the initial state at room temperature (mode A).
2. Holding specimens in the medium of liquid nitrogen for 60 min –subsequent static stretching of specimens to failure (mode B).

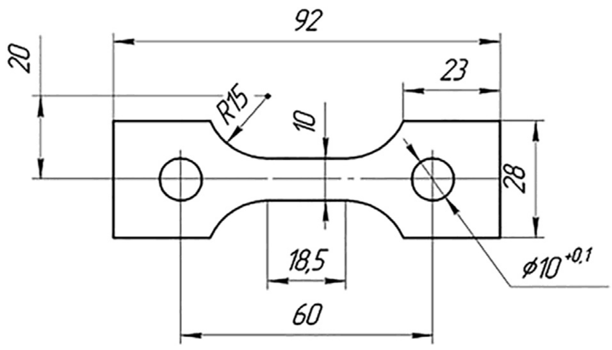

Fig. 2. Test specimen.